

The Ultra Cool Brown Dwarf Companion of WD 0806–661: Age, Mass, and Formation Mechanism

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ABSTRACT

We have combined multi-epoch images from the Infrared Side Port Imager on the CTIO 4-meter telescope to derive a $3\text{-}\sigma$ limit of $J = 21.7$ for the ultra cool brown dwarf companion to WD 0806–661 (GJ 3483). We find that $J - [4.5] > 4.95$, redder than any other brown dwarf known to date. With theoretical evolutionary models and ages $1.5 - 2.7$ Gyr, we estimate the brown dwarf companion to have mass $< 10 - 13 M_{Jup}$ and temperature $\lesssim 400$ K, providing evidence that this is among the coolest brown dwarfs currently known. The range of masses for this object is consistent with that anticipated from Jeans-mass fragmentation and we present this as the likely formation mechanism. However, we find that substellar companions of similar mass ($\sim 7 - 17 M_{Jup}$) are distributed over a wide range of semi-major axes, which suggests that giant planet and low-mass brown dwarf formation overlap in this mass range.

Subject headings: binaries: visual — brown dwarfs — planetary systems

1. Introduction

The first examples of the low-temperature L- and T-spectral classes were discovered as companions to stars (Becklin & Zuckerman 1988; Nakajima et al. 1995). The upper temperature limit for a Y-type object is not known; though it is expected to be < 500 K, when water vapor is predicted to condense (see Figure 2 in Burrows et al. 2003). Wide-field

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searches for low temperature T (and Y) dwarfs are currently in progress and several very cool objects have been found at temperatures of: ~ 570 K (Burningham et al. 2009), $550 - 500$ K (Leggett et al. 2009), $500 - 400$ K (Lucas et al. 2010), and < 500 K (Eisenhardt et al. 2010). However, the spectra of those objects (when available) do not differ substantially from late T-dwarfs. An object comoving with WD 0806–661 could represent the coolest substellar companion observed to date (Luhman et al. 2011). While no spectrum has yet been obtained, this could very well be the first example of the Y spectral class.

This Letter presents an upper limit at J-band to the substellar companion to WD 0806–661 (GJ 3483). Because the ‘WD’ designation is used exclusively for white dwarfs (E. Sion 2011, private comm.), we suggest the companion be referred to as GJ 3483B rather than WD 0806–661B, as adopted in the discovery paper (Luhman et al. 2011). We will use GJ 3483 and GJ 3483B throughout this Letter. We discuss what constraints our upper limit places on the object’s mass and temperature as well as how it ties in to other imaged low-mass companions. This object, and similar low-mass companions, probably formed at large separations from their primary star via Jeans-mass fragmentation (Low & Lynden-Bell 1976) rather than been scattered out via planet-planet interactions.

2. Observations

As part of an ongoing imaging campaign to search for wide separation low-mass companions to nearby, old white dwarfs, we observed GJ 3483 using the Infrared Side Port Imager (ISPI, van der Blik et al. 2004) on the CTIO 4-m Blanco telescope. Observations were carried out on UT 2009-03-16, 2009-03-17, 2010-04-03, and 2010-04-05, each lasting 3240 seconds (3 sets of 3×3 dithers with individual exposure times of 120 seconds) and covering a field of view of approximately $10' \times 10'$. Conditions were generally good with seeing $\sim 1''$ at J-band ($\sim 1.3''$ on 2009-03-17) and clear (except for thin clouds on 2009-03-16). Data reduction was carried out in the usual manner using standard IRAF routines¹. The brown dwarf companion observed by Spitzer (Luhman et al. 2011) was not detected in any of the individual nights.

To obtain a deeper J-band limit, we coadded data from the four nights together. Because the white dwarf has proper motion of $(+340.3, -289.6)$ mas yr^{−1} (Subasavage et al. 2009), we shifted the 2009 data by 1 pixel in both R.A. and Decl. to match the white dwarf’s

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motion (the ISPI plate scale is $0.3'' \text{ pix}^{-1}$). Individual nights were weighted by the square of the signal-to-noise of well-detected 2MASS stars. Our coadded, 3.5-hour image is displayed in Figure 1 alongside the 2009 $4.5\mu\text{m}$ Spitzer field from program 60160 (M. Burleigh) and it is clear we do not detect the companion brown dwarf. To estimate a limiting magnitude, we generated synthetic stars in 0.1 magnitude bins ranging from $J=20.6$ to 22.6 using IRAF/DAOPHOT’s `addstar` routine with a PSF derived from stars in our field. PSF fitting was performed on these synthetic stars, which allows us to estimate a $3\text{-}\sigma$ limit of $J = 21.7$ for this coadded exposure, 1.7 magnitudes fainter than the limit provided by Luhman et al. (2011).

3. Results

With our upper limit of $J = 21.7$, we estimate $J - [4.5] > 4.95$, nearly two magnitudes greater than the value quoted in Luhman et al. (2011) and redder than any other T-dwarf currently known. Figure 2 illustrates the trend of decreasing absolute $4.5\mu\text{m}$ magnitude for known T-dwarfs as a function of $J - [4.5]$ color. Our upper limit for GJ 3483B is consistent with the T-dwarf trend, though it could be redder (and, thus, as faint as $J \sim 23 - 24$). The initial-final mass relationships in Catalán et al. (2008, and references therein) along with the estimated white dwarf mass of $0.62 \pm 0.03 M_{\odot}$ (Subasavage et al. 2009) suggest the progenitor mass was $2.0 \pm 0.3 M_{\odot}$ with a main sequence lifetime of $1.3^{+0.7}_{-0.5}$ Gyr (Catalán et al. 2008, and references therein; S. Leggett 2011, private comm.). With the cooling age of 670 Myr derived in Subasavage et al. (2009), this implies a total age of 1.5 to 2.7 Gyr. Based on our $3\text{-}\sigma$ limit, an age of 1.5 Gyr, and theoretical evolutionary models from Burrows et al. (2003) and Baraffe et al. (2003), we estimate a mass of $< 10 M_{Jup}$ and temperature < 410 K. However, with an age of 2.7 Gyr, we find the companion has a mass of $< 13 M_{Jup}$ and temperature < 400 K.

The IRAC $4.5\mu\text{m}$ photometric magnitude of 16.72 (Luhman et al. 2011) can also be used to derive the mass and temperature of GJ 3483B. With an age of 1.5 Gyr, we find the Burrows et al. (2003) models predict a mass of $\sim 6 M_{Jup}$ and temperature ~ 330 K. With the upper age limit of 2.7 Gyr, we find mass and temperature of $\sim 10 M_{Jup}$ and ~ 350 K. These model temperatures are somewhat warmer than the value Luhman et al. (2011) present (~ 300 K). While the uncertainty in age and thus the mass of GJ 3483B are substantial, the range of implied masses is consistent with those anticipated from Jeans-mass fragmentation (see Section 4). That is, the mass of GJ 3483B is unlikely to be much smaller than $\sim 7 M_{Jup}$. The range in mass and temperature ($6 - 10 M_{Jup}$, $330 - 350$ K) for GJ 3483B are comparable to those of CFBDSIR J1458+1013B ($6 - 15 M_{Jup}$, 370 ± 40 K),

another recently discovered ultra cool companion (Liu et al. 2011).

4. Discussion

Companions with masses less than $\sim 20 M_{Jup}$ have been imaged in only a handful of systems (listed in Table 1) and most have masses between 7 and $15 M_{Jup}$. As described in Zuckerman & Song (2009), objects of mass $\sim 15 M_{Jup}$ would require at least 2 Gyr to cool down to ~ 500 K, which is usually taken as the temperature in which the Y-dwarf spectral type will appear. Binaries with brown dwarf secondaries having masses larger than $15 M_{Jup}$ are somewhat more common than the few listed in Table 1 (see Table 2 in Zuckerman & Song 2009), but for a $\sim 25 M_{Jup}$ object to cool to 500 K it must be at least 7 Gyr old, according to the Burrows et al. (2003) models. Hence the coolest companions are more likely to be found in relatively old systems.

A handful of white dwarfs are known to host widely separated brown dwarf companions (see Table 2). While a few other WD+BD pairs are known, these are unresolved systems whose separations are a few AU or less (GD 1400, Farihi & Christopher 2004; WD 0137-349, Maxted et al. 2006). The separations among the resolved WD+BD pairs is generally on the order of ~ 1000 's of AU, albeit with low number statistics. Companions around white dwarfs are expected (and observed, see Farihi et al. 2010) to have a bimodal distribution in their orbital semi-major axes (Nordhaus et al. 2010). Those orbiting close to the main sequence star will spiral in via tidal dissipation (Hansen 2010). More widely separated companions (such as most of those in Table 1) will undergo orbital expansion following post main sequence mass loss from the white dwarf progenitor. Assuming the mass loss was adiabatic, which is almost certainly true (the orbital period is short compared to the time frame of mass-loss), the ratio of semimajor axes (a) between the white dwarf and main sequence phases should be identical to the inverse ratio of white dwarf and main sequence masses, or $a_{wd} = a_{ms} M_{ms} / M_{wd}$ (Jeans 1924). As previously mentioned, GJ 3483 has a final mass of $0.62 M_{\odot}$ and initial mass of $2.0 M_{\odot}$. If we assume the 2500 AU projected separation corresponds to a semi-major axis, then while on the main sequence this binary would have had $a \sim 780$ AU, consistent with the values in Table 1.

The commonly accepted mass limits for brown dwarfs are 13 and $75 M_{Jup}$, where an object would fuse deuterium, but not hydrogen. In this case, planets (in addition to orbiting stars) would have masses below $\sim 13 M_{Jup}$. However, Jeans fragmentation can produce gravitationally collapsing clumps with masses as low as $\sim 7 M_{Jup}$ (Low & Lynden-Bell 1976). Typically, these fragments will have average separations of a few 100 AU. As seen in Table 1, there are several imaged systems with masses lower than $\sim 15 M_{Jup}$ that orbit their

host stars at these wide separations. Giant planets, on the other hand, can form via core accretion in a disk fairly close to the star (Pollack et al. 1996; Kenyon & Bromley 2009) or via gravitational instability at larger separations so long as the disk is sufficiently massive (Boss 1997). Numerical simulations, however, have shown that planet formation via core accretion does not generally occur beyond 35 AU (Dodson-Robinson et al. 2009, but see also Currie et al. 2011 for contrasting arguments). Gravitational instability could create massive planets at larger semi-major axes, but only for the most massive disks would one expect planets to form at ~ 100 AU (see Rafikov 2005, and references therein).

Figure 3 shows the separations and masses of low mass companions from Table 1 and extrasolar planets from the Exoplanet Orbit Database (Wright et al. 2010). The population of exoplanets extends to lower masses and shorter separations (semi-major axes), but is not displayed here. As mentioned in the preceding paragraphs, one would not expect giant planets to form at separations larger than ~ 100 AU. However, it appears that for objects $\sim 7 - 17 M_{Jup}$, companions are distributed in a wide range of separations, reaching as far as ~ 1000 AU. Planet-planet scattering could conceivably eject objects out to these large separations (Veras et al. 2009; Dodson-Robinson et al. 2009, and references therein). Since lower mass planets are more readily scattered out to larger orbits than more massive objects, one would expect to see a larger number of low mass planets at large separations. However, numerous adaptive optics searches for companions have been performed, yet very few low mass objects have been found despite sensitivities to objects with masses $\gtrsim 3 M_{Jup}$ at separations $\gtrsim 40$ AU (Chauvin et al. 2010; Nielsen & Close 2010; and references therein). Additionally, while many giant planets have been detected with radial velocity searches, there is a lack of $> 13 M_{Jup}$ substellar companions within $\lesssim 5$ AU, despite being sensitive to such objects (the well-known brown dwarf desert, see Marcy & Butler 2000). The paucity of low mass companions at large separations contrasts with both theoretical expectations and detected giant planets at $a \lesssim 5$ AU and suggests that planet-planet scattering is not a common mechanism to move large, $\sim 7 - 17 M_{Jup}$ mass companions, such as GJ 3483B and those listed in Table 1, to large separations.

The low mass, directly imaged companions with separations $\lesssim 100$ AU are worth mentioning, as they may be notable exceptions to Jeans fragmentation: HR 8799b,c,d,e; β Pic b; and 2M1207b. In the case of HR 8799 and β Pic, the planetary mass companions orbit relatively close to their A-type stars, which possess extended circumstellar disks (see Rhee et al. 2007). The brown dwarf 2M1207 also possesses a disk close to the primary ($R \lesssim 0.2$ AU; Riaz et al. 2006), but the low mass companion orbits beyond it at 46 AU. While the disks around A-type stars can be massive enough to form giant planets at large separations, it is unlikely that a brown dwarf can possess a similarly massive disk. This suggests that, while low mass brown dwarf formation and planet formation operate on different scales, formation

mechanisms for companions with masses $\lesssim 13 M_{Jup}$ begin to overlap (see discussions in Currie et al. 2011 and Kratter et al. 2010). The discovery of additional low mass, widely separated companions will play a key role in our understanding of giant planet and low mass brown dwarf formation.

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Table 1: Lowest mass imaged companions

Object	Sp. Type		Age (Myr)	M_{pri} (M_{\odot})	M_{sec} (M_{Jup})	Sep.		Ref.
	Primary	Sec.				(AU)	($''$)	
2M1207–39	M8	L5	8	0.025	6	46	0.9	1
AB Pic	K2V	L1	30	0.84	14	248	5.5	1
Oph 11	M9	M9.5	5	0.0175	15	237	1.6	1
GQ Lup	K7V	L1.5	3?	0.7	17	100	0.7	1
HN Peg	G0V	T2.5	200	1.0	16	795	43.2	1
HR 8799	A5V	late-L	30	1.5	5	68	1.7	2,3
					7	38	1.0	
					7	24	0.6	
					7	14.5	0.4	
β Pic	A5V	late-L	12	1.75	~ 9	8–15	0.3	4
Ross 458	M0.5+M7	T8	150 – 800	0.6+0.08	6–11	1168	102	5,6
GSC 06214–00210	M1	M8–L4	5	0.6	14	319	2.2	7
GJ 3483	DQ	Y?	1500–2700	0.62	$\sim 6 - 10$	2500 ^a	130	8,9

^aWhile on the main sequence, the orbital separation for GJ 3483B may have been ~ 780 AU (see Section 4). **References:** 1– Zuckerman & Song (2009); and references therein, 2– Marois et al. (2008), 3– Marois et al. (2010), 4– Lagrange et al. (2010), 5– Goldman et al. (2010), 6– Burgasser et al. (2010), 7– Ireland et al. (2011), 8– Luhman et al. (2011), 9– This work.

We do not list the recently announced 2.6 AU-separation CFBDSIR J1458+1013AB system as it lacks a firm age estimate and thus has widely varying masses for the primary and secondary, both of which are brown dwarfs with likely masses $< 20 M_{Jup}$ (Liu et al. 2011). A few other low-mass companions are known, but either with uncertain masses that could well be above $\sim 20 M_{Jup}$ (for example, GJ 758B at 10–40 M_{Jup} ; Thalmann et al. 2009) or the possibility that the two components could be independent members of the same co-moving region (such as 2M J04414489+2301513, 1RXS J160929.1–210524, and CT Cha; Todorov et al. 2010; Lafrenière et al. 2010; Schmidt et al. 2008). The measured separations are lower limits to the semi-major axes which, on average, will be somewhat larger than the observed separations.

Table 2: Spatially resolved WD+BD pairs

Object	Sp. Type		Age (Gyr)	M_{pri} (M_{\odot})	M_{sec} (M_{Jup})	T_{eff} (K)	Sep.		Ref.
	Primary	Sec.					(AU)	($''$)	
GD 165	DA	L3	1.2 – 5.5	0.56 – 0.65	~ 75	1900	140	4	1,2
PHL 5038	DA	L8	1.9 – 2.7	0.57 – 0.87	60	1450	55	0.94	3
LSPM 1459+0857AB	DA	T4.5	> 4.8	0.585	64 – 75	1350	16500 – 26500	365	4
GJ 3483	DQ	Y?	1.5 – 2.7	0.62	$\sim 6 - 10$	340	2500	130	5,6

References: 1– Zuckerman & Becklin (1992), 2– Kirkpatrick et al. (1999), 3– Steele et al. (2009), 4– Day-Jones et al. (2011), 5– Luhman et al. (2011), 6– This work.

Temperatures listed are averages of the range provided in the references (including GJ 3483B) for the secondary in the system. A range of separation is listed for LSPM 1459+0857AB as the distance is determined photometrically assuming the object is either single or an unresolved binary (Day-Jones et al. 2011). Separations for these WD+BD pairs would have been smaller while on the main sequence, typically by a factor of 2 to 4 (see Section 4).

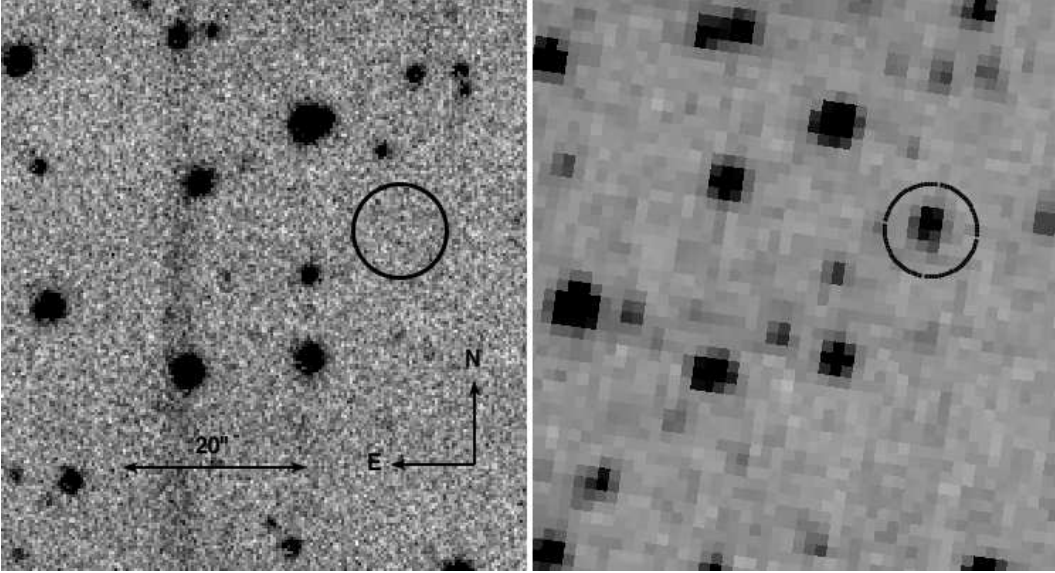


Fig. 1.— Co-added (3.5 hours) CTIO ISPI J-band field (left) and Spitzer IRAC $4.5\mu\text{m}$ field (right); the circle denotes the location of GJ 3483B.

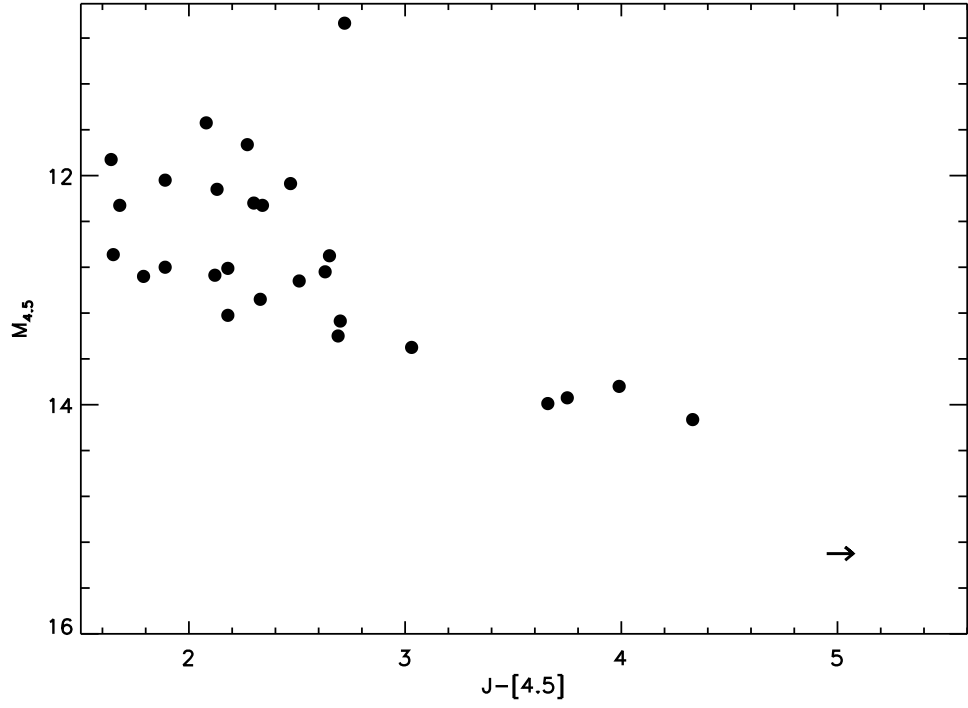


Fig. 2.— $M_{4.5}$ versus $J - [4.5]$ for T dwarfs with measured distances and IRAC photometry from Lucas et al. (2010) and Leggett et al. (2010). GJ 3483B is indicated with a right-pointing arrow whose base corresponds to our upper limit of $J - [4.5] = 4.95$. It is the reddest brown dwarf currently known.

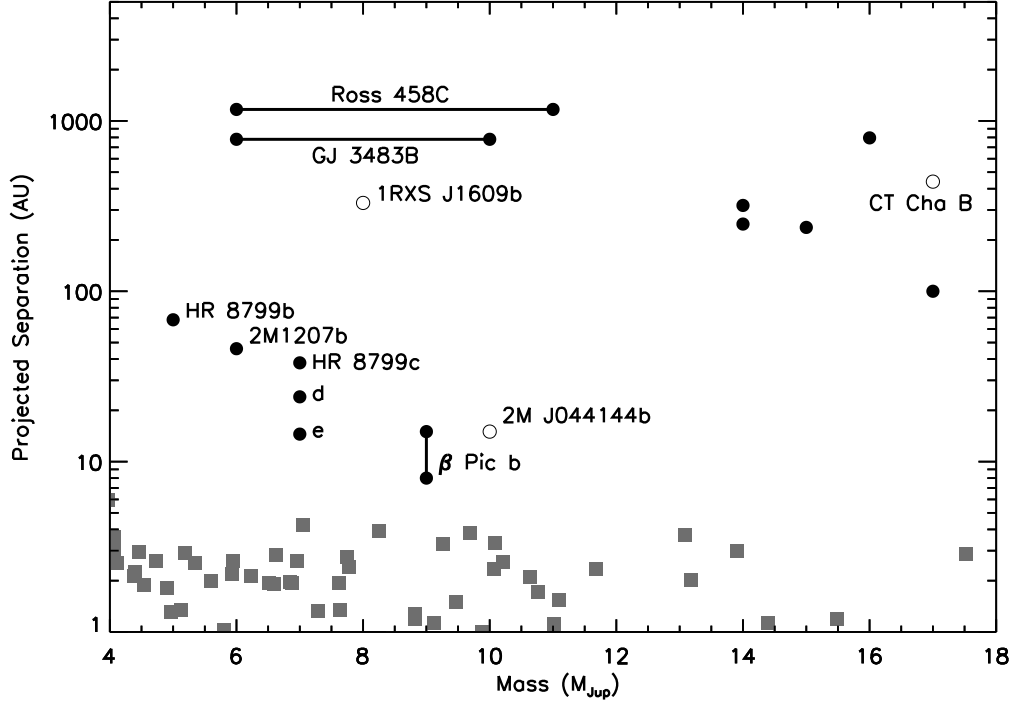


Fig. 3.— The lowest mass imaged companions to date (listed in Table 1). GJ 3483B is plotted at its expected location while the primary was on main sequence (~ 780 AU; see Section 4); we also indicate the mass range ($6 - 10 M_{Jup}$). Gray squares denote extrasolar planet candidates from the Exoplanet Orbit Database (Wright et al. 2010); plotted masses are $M \sin i$ and could be larger than shown. CFBDSIR J1458+1013B is not shown; its separation is 2.6 AU, but has a broad range for the mass ($\sim 6 - 15 M_{Jup}$; Liu et al. 2011). CT Cha B, 1RXS J1609b, and 2M J044144b (whose mass may be $5-10 M_{Jup}$, though for clarity we only display the higher value from Todorov et al. 2010) are displayed as open circles as it’s not yet known if these are bound (see footnote to Table 1).